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Evaluation of energy efficiency of various biogas production and utilization pathways

Martina Pöschl [a,*], Shane Ward [a], Philip Owende [a,b]

[a] Charles Parsons Energy Research Programme, Bioresources Research Centre, School of Agriculture, Food Science and Veterinary Medicine, University College Dublin, Belfield, Dublin 4, Ireland
[b] School of Informatics and Engineering, Institute of Technology Blanchardstown, Blanchardstown Road North, Dublin 15, Ireland

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ABSTRACT

The energy efficiency of different biogas systems, including single and co-digestion of multiple feedstock, different biogas utilization pathways, and waste-stream management strategies was evaluated. The input data were derived from assessment of existing biogas systems, present knowledge on anaerobic digestion process management and technologies for biogas system operating conditions in Germany. The energy balance was evaluated as Primary Energy Input to Output (PEIO) ratio, to assess the process energy efficiency, hence, the potential sustainability. Results indicate that the PEIO correspond to 10.5–64.0% and 34.1–55.0% for single feedstock digestion and feedstock co-digestion, respectively. Energy balance was assessed to be negative for feedstock transportation distances in excess of 22 km and 425 km for cattle manure and for Municipal Solid Waste, respectively, which defines the operational limits for respective feedstock transportation. Energy input was highly influenced by the characteristics of feedstock used. For example, agricultural waste, in most part, did not require pre-treatment. Energy crop feedstock required the respect cultivation energy inputs, and processing of industrial waste streams included energy-demanding pre-treatment processes to meet stipulated hygiene standards. Energy balance depended on biogas yield, the utilization efficiency, and energy value of intended fossil fuel substitution. For example, obtained results suggests that, whereas the upgrading of biogas to biomethane for injection into natural gas network potentially increased the primary energy input for biogas utilization by up to 100%; the energy efficiency of the biogas system improved by up to 65% when natural gas was substituted instead of electricity. It was also found that, system energy efficiency could be further enhanced by 5.1–6.1% through recovery of residual biogas from enclosed digestate storage units. Overall, this study provides bases for more detailed assessment of environmental compatibility of energy efficiency pathways in biogas production and utilization, including management of spent digestate.

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Contents

1. Introduction . . . 3306
2. Material and methods . . . 3306
   2.1. Background data . . . 3306
   2.2. Data analysis . . . 3307
   2.3. Description of scenarios analysed . . . 3308
      2.3.1. Feedstock digestion scenarios . . . 3308
      2.3.2. Biogas utilization scenarios . . . 3309
      2.3.3. Waste stream scenarios . . . 3309
3. Rationalisation of study assumptions . . . 3309
   3.1. Determination of biogas yield by feedstock options . . . 3309
   3.2. Considerations in feedstock supply logistics . . . 3310
   3.3. Energy input to feedstock transportation . . . 3310
   3.4. Biogas plant operation . . . 3310

* Corresponding author. Tel.: +49 861 9095621.
E-mail address: martina.poeschl@web.de (M. Pöschl).

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3.5. Biogas utilization . . . 3311
3.5.1. Electricity generation . . . 3311
3.5.1.1. Combined Heat and Power (CHP) generation . . . 3311
3.5.1.2. Fuel cell technology . . . 3311
3.5.1.3. Stirling engines . . . 3311
3.5.1.4. Micro gas turbines . . . 3312
3.5.2. Heat generation . . . 3312
3.5.2.1. Process heat demand of biogas system . . . 3312
3.5.2.2. Heat utilization via district heating network . . . 3312
3.5.2.3. Organic Rankine Cycle process . . . 3312
3.5.2.4. Other areas for biogas utilization . . . 3312
3.5.3. Upgrading of biogas . . . 3312
3.6. Processing and handling of digestate . . . 3312
4. Results and discussion . . . 3313
4.1. Consideration of the single feedstock digestion scenario . . . 3313
4.2. Consideration of feedstock co-digestion scenario . . . 3314
4.3. Consideration of biogas utilization scenario . . . 3315
4.4. Consideration of waste stream scenario . . . 3317
5. Conclusions . . . 3319
Acknowledgement . . . 3319
References . . . 3319

1. Introduction

The European Energy Policy is underpinned by: need to minimise exposure to volatility of fossil fuel prices; need for reduction of greenhouse gas (GHG) emissions by using less, cleaner, and locally produced energy, including the energy recovery from waste, and need for more competitive energy markets to stimulate technology innovation and jobs [1]. In Germany, the focus is to increase renewable energy utilization from the current 9.1% to 20% by 2020. Consequently, the government developed an integrated energy and climate program for structured GHG reduction, in which 25–30% of electricity and 14% of heat requirements is to be generated from renewable sources [2]. Biogas production by anaerobic digestion (AD) of organic waste is key to meeting these targets [3]. The estimated biogas production potential, based on feedstock resource availability in Germany is 417 PJ per annum [4]. Over 80% of the estimated potential derives from agricultural resources, including farm waste, crop residues, and dedicated energy crops (96.5, 13.7, and 236 PJ per annum, respectively). To realize this potential, enhancement of incentives and minimisation of barriers to expansion of biogas production will be required, including: (i) simplifying the procedures in biogas plant implementation process; (ii) enhanced Research and Development on feedstock co-digestion, especially of agri-food industry waste and Municipal Solid Waste (MSW) streams; and (iii) enhancement of biogas utilization through provision of incentives to biogas plants, e.g., economic feed-in tariffs and access to electricity and gas grid infrastructure [5].

Biogas is arguably a more versatile renewable energy source (*cf.* wind and solar energy), due to its determinate energy value and ease of storage, hence, potential utilization is significantly independent of factors such as geographical location and season [6]. It can be used directly for heating and electricity generation, and as substitute for fossil fuel applications, e.g., transport fuel [4,7,8]. The potential utilization of the digestate [9] as fertilizer can also reduce dependence on energy intensive mineral fertilizers, to further mitigate GHG emissions [10]. Since the activation of the ban on landfilling of organic waste in Germany [11], the AD process provides a viable waste management option [12], but sustainable biogas utilization requires maintenance of a positive life-cycle energy balance.

Analyses of energy balance in the life-cycle of biogas systems that have been reported to-date often lack bases for comparison, due to varying accounting system and boundaries [13]. In particular, many studies on energy balance have focused on specific raw material [14–22], specific biogas systems [6,16,18,23–25], different waste management strategies [26–28], and on specific utilization options for biogas [29–31]. To the authors' knowledge, only the study by Berglund and Börjesson [13] has addressed the entire life-cycle of different biogas systems. However, Berglund and Börjesson [13] identified the main factors affecting the energy input/output ratio for biogas systems, but did not attempt to correlate these to the primary energy output. None of the analyses reviewed have coupled multiple feedstock scenarios to viable energy conversion pathways to assess: (i) impact of plant locations to minimise GHG emissions through reduced fossil fuel usage and elimination of existing technical and policy obstacles [5]; (ii) potential for integrated efficiency enhancement for reliability and to minimise cost; and (iii) overall system sustainability.

The objective of this study was to evaluate the impact of feedstock (single and co-digested) and process chains (production, conversion and utilization) on energy balance of biogas systems. It was to evaluate any latent factors determining the Primary Energy Input Output (PEIO) ratio, which could be used for further efficiency enhancement.

2. Material and methods

Fig. 1 shows the study boundary, encompassing; feedstock resources, harvesting and transport, biogas plant operation, biogas-to-energy conversion technologies, and digestate handling. Analyses were based on literature data relevant to conditions in Germany.

2.1. Background data

The analyses considered the three main feedstock material flows, including, agricultural waste, energy crops, and Municipal Solid Waste (MSW) and residues from food industry [32,33]. The number of biogas plants in Germany has increased by almost 2000 in the last 5 years, with an average output of 500 kW_{el}. Small-scale biogas systems (<500 kW_{el} installed capacity) are designated to handle predominantly agricultural waste and energy crop feedstock [34] with localized energy utilization, but with option for electricity feed-in to the national grid. Large-scale biogas

Nomenclature

AD	anaerobic digestion	MPa	megapascal
CaO	lime	MSW	Municipal Solid Waste
CH_4	methane	MW h	megawatt hour
CHP	Combined Heat and Power System	N	nitrogen
DM	dry matter content, dry mass	Nm^3	normal cubic metre (biogas yield)
EEG	Renewable Energy Sources Act	NO_x	nitrogen oxides
GHG	greenhouse gas	ORC	Organic Rankine Cycle process
GJ_{PE}	gigajoule of primary energy source	P_2O_5	phosphate
K_2O	potassium oxide	PE	primary energy
kW_{el}	kilowatt electricity load	PEIO	Primary Energy Input Output ratio
kW_{th}	kilowatt thermal load	PJ	petajoule
kW h_{el}	kilowatt hour electricity load	t	tonne of fresh mass
kW h_{th}	kilowatt hour thermal load	t_{DM}	tonne of feedstock dry matter
MCFC	Molten Carbonate Fuel Cell	t_{VS}	tonne of volatile solids
MJ_{PE}	megajoule of primary energy source	t km	tonne kilometre

plants ($\geqslant$500 kW_{el} installed capacity) co-digest agricultural feedstock with industrial waste and MSW, with capability to feed-in biomethane to the natural gas grid. Large-scale biogas plants typically produce more than 1.8 million m^3 of biogas per annum, with feedstock handling capacity of ca. 20,000 tonnes per annum, as distinct from small-scale biogas plants with typically up to 10,000 tonnes per annum.

Table 1 summarizes the primary energy inputs to mineral based resources considered. Primary energy refers to energy that has not undergone any conversion or transformation process. Process analysis for agricultural and MSW waste streams and food industry residues considered the energy inputs for feedstock collection, transport and pre-treatment. Analyses for energy crops considered the entire supply chain from planting and cultivation, through harvesting and transport processes. Cultivation was on arable land with no conflict with food and/or fodder production, and therefore opportunity cost of land could be ignored [35,36]. Options in biogas utilization included; upgrade to biomethane for transport fuel or fuel cell technology, and conversion technologies including, CHP, Stirling engine, Organic Rankine Cycle, and Micro gas turbine. Digestate disposal, and treatment and handling options such as separation, composting or drying the solid matter to ease transportation were also considered [32,37].

2.2. Data analysis

Energy balance was evaluated as ratio of Primary Energy Input to Output (PEIO). Energy input was evaluated as the sum of energy inputs to; crop cultivation and feedstock pre-treatment, feedstock collection and transport, biogas plant operation, biogas utilization and digestate processing and handling. Energy output was evaluated as the sum of potential energy conversion from the biogas yield from respective feedstocks. The lower the PEIO value, the higher the efficiency of the system chain, and energy output is deemed negative for PEIO exceeding unity. It was assumed that the potential electricity and heat generation, and biomethane and digestate yields would substitute equivalent energy generated from specific fossil fuel mix and crop production inputs in Table 1.

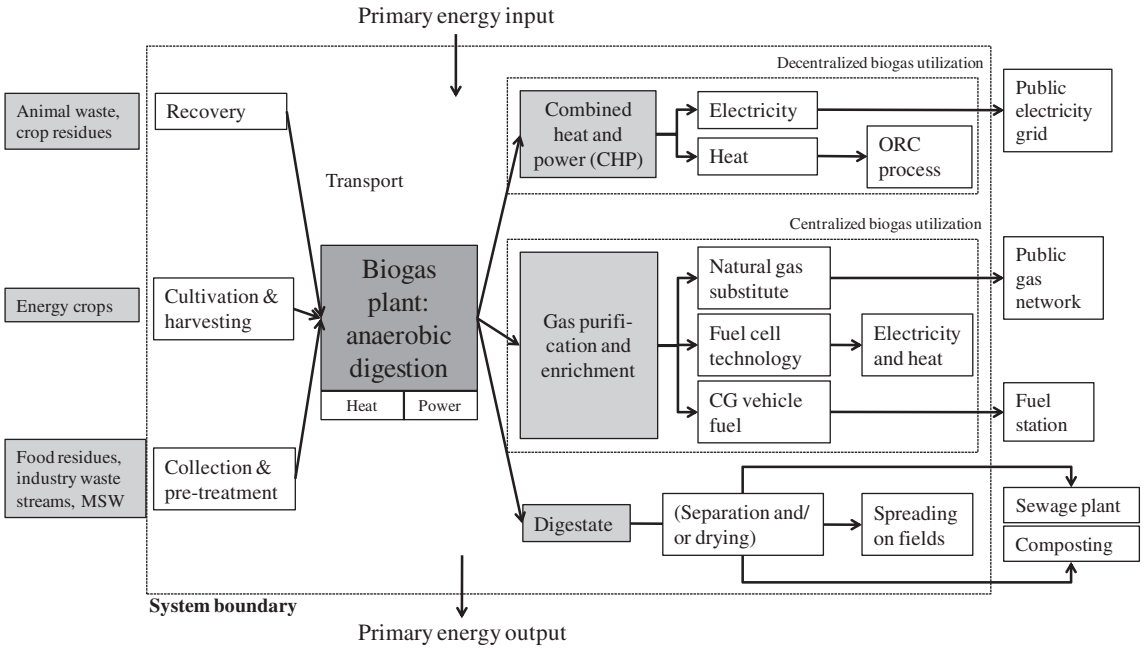

Fig. 1. Study boundary showing material and energy flows.

Table 1
Primary energy inputs to production of fossil fuel based resources considered in this study.

Specific energy value	Material/process	Energy input
Diesel fuel (MJ_{PE} l^{-1})[a]	Production and distribution	63
Electricity (MJ_{PE} MJ^{-1})[a]	Electricity mix for Germany	2.654
Natural gas (MJ_{PE} MJ^{-1})[b]	Production and distribution	45.6
Heating (MJ_{PE} MJ^{-1})	Biogas[c]	1.3
	Natural gas, heating oil and hard coal[b]	44.2
Seeds (MJ_{PE} kg^{-1})[a]	Grass	18.14
	Corn	9.58
	Wheat	3.48
Chemical fertilizer (MJ_{PE} kg^{-1}) [a]	Nitrogen N	53
	Phosphate P_2O_5	20.7
	Potassium oxide K_2O	7.7
	Lime CaO	0.7
Pesticides (MJ_{PE} kg^{-1})[a]		1.184

[a] Data adopted from [15].
[b] Data adopted from [83].
[c] Data adopted from [13].

2.3. Description of scenarios analysed

Realistic feedstock scenarios, biogas utilization scenarios, and waste management scenarios were analysed to determine the energy performance of systems that are commonly used in Germany [38]. Wet mesophilic two-stage AD process depicted in Fig. 2 was assumed. Transport distance between biogas plant and origin of feedstock was assumed to be within 5 km, while digestate disposal was within a 10 km radius. Defined base case scenarios were used to assess the energy performance of alternative biogas systems.

2.3.1. Feedstock digestion scenarios

Single feedstock digestion was only applicable to small-scale biogas plants, and base case was cattle manure [38]. Considering the possible variations in feedstock availability, coupled with the importance of energy efficient transportation, and AD process considerations, single feedstock digestion is considered unsustainable for large-scale plants. For example, sub-optimal composition of trace elements in single feedstock can impede the AD process [39]. Similarly, rapid acidification of easily degradable feedstock, e.g., food residues, may result in unsuitable conditions capable of stalling the AD process [40]. Consequently, most biogas systems in Germany co-digest between three and five feedstock [38]. Table 2 represents several co-digestion scenarios for small (Base SS, SS-1, SS-2) and large-scale biogas plants (Base LS, LS-1, LS-2) investigated to determine their impacts on the PEIO and the characteristic proportion of energy input to AD process steps. Biogas yield in co-digestion was assumed to be 10% higher than in single feedstock digestion (Fig. 3).

Between 75% and 80% of biogas plants co-digest cattle manure and corn silage [38], therefore the combination was used as base

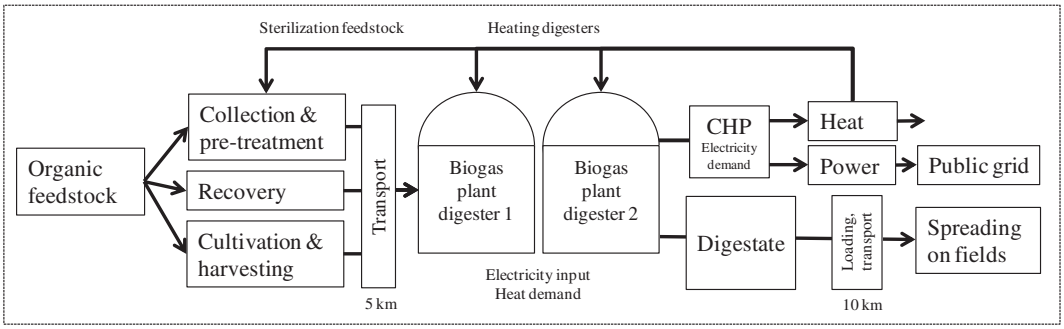

Fig. 2. Schematic of biogas-to-CHP process chain considered in single feedstock digestion and feedstock co-digestion scenarios.

Table 2
Different co-digestion scenarios analysed as typical examples of systems in operation (Germany).

AD feedstocks	Small-scale biogas systems (SS) [a]			Large-scale biogas systems (LS) [a]		
	Base case (Base SS) [b,c]	SS-1 [d]	SS-2 [e]	Base case (Base LS) [f]	LS-1 [f]	LS-2 [g]
Cattle manure	55%	30%	40%	13%	25%	
Straw			5%			
Corn silage	45%	50%			35%	
Grass silage		10%			18%	
Whole wheat plant silage		10%			22%	
Municipal Solid Waste				14%		90%
Food residues			20%	10%		6%
Pomace			10%			
Slaughterhouse waste (paunch content)			15%	14%		4%
Grease separator sludge			10%	49%		

[a] Small and large-scale biogas systems typically handle up to 10,000 and at least 20,000 tonnes feedstock per annum, respectively.
[b] Approximately 75% of biogas systems in Germany use cattle manure in co-digestion for biogas production with an average proportion of 55% [38]; The amended EEG includes an liquid manure bonus for using at least 30% of liquid manure for biogas production up to 150 kW_{el} [41].
[c] Approximately 80% of biogas systems in Germany use corn silage in co-digestion for biogas production [38], resulting from existing renewable energy resources incentive under the EEG.
[d] Data based on [84].
[e] Data based on [85].
[f] Data based on [86].
[g] Data based on [87].

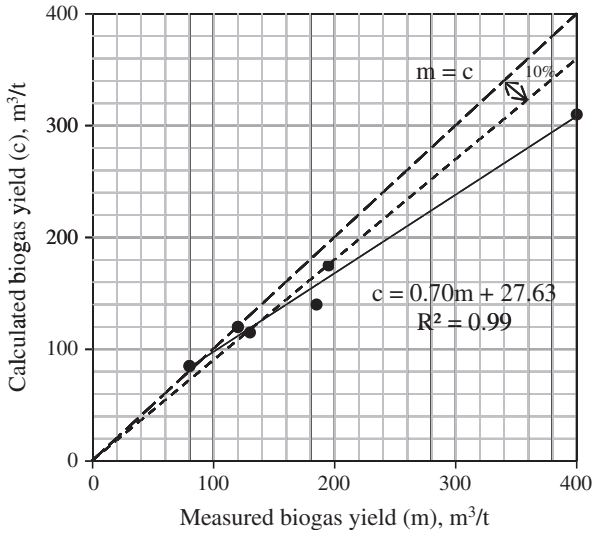

Fig. 3. Comparison of calculated biogas yield by feedtock proportion in feedstock co-digestion mix against measured biogas yield for co-digestion in full-scale biogas plants. The calculated values are based on data from the Association of Technology and Structures in Germany [49], whereas measured values are based on realized biogas plants in Germany [38,94].

case for co-digestion in small-scale plants (Base SS). Co-digestion of agricultural feedstock and industrial waste streams and MSW is standard for large-scale biogas plants handling ca. 20,000 tonnes per annum, which was base feedstock for Base LS scenario (Table 2).

2.3.2. Biogas utilization scenarios

Decentralized power generation with CHP units and feed-in of excess capacity to the national grid is the most common biogas utilization pathway [5,41]. In this study, additional biogas utilization pathways were considered for their potential impact on energy efficiency and mitigation of environmental impacts by substituting different fossil fuels in addition to electricity generation (Table 3). For example, utilization of biogas generated by small-scale plant, Base SS-d, included CHP generation and secondary use of waste heat in Organic Rankine Cycle generator to enhance system efficiency.

2.3.3. Waste stream scenarios

Different waste stream scenarios were used to assess the potential impact on PEIO (Table 4). Spreading of untreated digestate on arable land was only acceptable if the amount did not exceed soil nutrient limits (Base LS). Separation of digestate into liquid and solid fraction to minimise handling, and alternative drying/composting of solid fraction for use as substitute for chemical fertilizer were considered. Potential impact of recovering residual biogas from digestate storage was also considered.

3. Rationalisation of study assumptions

3.1. Determination of biogas yield by feedstock options

The feedstock analysis considered ready availability and suitability for AD process (Table 5). The unused feedstock potential of cattle manure in Germany is estimated at 90%, hence, it was considered to be the most suitable base feedstock [4,42]. Recovery of agricultural residues such as straw also has environmental advan-

Table 3
Different biogas utilization scenarios analysed. Small-scale biogas systems normally utilize the biogas at source, and in contrast to large-scale plants which prefer transmission for wider application.

Biogas utilization pathways	Small-scale plants							Large-scale plants					
	Base SS	*a*	*b*	*c*	*d*	*e*	*f*	Base LS	A(U)	B(U)[a]	C(U)	D(U)	E(U)
CHP	×	×	×	×	×			×		×			
External heat		×		×		×	×						×
Cooling energy			×	×									
ORC					×								
Stirling engine						×							
Micro gas turbine							×						
Gas grid injection									×	×			
Transport fuel											×		
Fuel cell												×	×

[a] The CHP unit here is specifically to provide heat for biogas production and upgrading processes.

Table 4
Different waste-stream management scenarios analysed. Limitation on the amount of nutrients that may be spread on agricultural land dictates the variations in digestate pretreatment and disposal technologies mainly for large-scale biogas systems.

Waste stream process	Variations analysed						
	Base LS	A(W)	B(W)	C(W)	D(W)	E(W)	F(W)
No treatment of digestate	×						
Separation by decanter technology		×	×	×			
Separation by screw-press technology					×	×	×
Spreading of liquid fraction	×						
Spreading of solid fraction		×	×	×	×	×	×
Drying of solid fraction (by waste heat of CHP)			×			×	
Composting of solid fraction				×			×
Substitute chemical fertilizer			×	×		×	×
Residual biogas utilization				(a)[a]	(b)[a]		

[a] Base LS-C(W) and -D(W) are additionally calculated with residual biogas utilization by covered digestate storage area, showing influences on PEIO, which are marked by initials (a) and (b).

Table 5
Estimated biogas yield and dry matter (DM) content of digestate by feedstock options adopted from [49], other data evaluated in this study.

Feedstocks	DM content feedstock[b] (%)	DM content digestate[c] (%)	Biogas yield ($m^3\ t_{DM}^{-1}$)	Methane content (%)	Energy content (GJ t_{DM}^{-1})
Cattle manure	8	4.3	297	55	5.9
Straw	86	81.6	341	51	6.2
Corn silage	35	11.1	576	52	10.8
Grass silage	25	9	492	54	9.5
Whole wheat plant silage	40	14.2	488	52	9.1
Municipal Solid Waste (MSW) [a]	40	31.8	308	60	6.6
Food residues	16	4	592	60	12.7
Pomace	22	4.5	510	52	9.5
Slaughterhouse waste (paunch content)	15	7.4	403	55	8.0
Grease separator sludge	5	1	900	68	22.0

[a] Compositions of MSW is highly variable and can significantly influence biogas yield [51].
[b] Fresh mass implies feedstock in consistence of origin, whereas dry matter (DM) is the result of fresh mass less the water content.
[c] Degradation of organic dry matter content from feedstock results in different dry matter content of digestate for single feedstock. Data based on [88].

tages in preventing nitrogen leakage into groundwater from decaying process [43]. Cultivation of energy crops such as corn, grass and wheat are subsidised therefore widely used in biogas production, and was assumed to conform to good agricultural practice [44,45].

Biogas yield is influenced by several process conditions, and variation up to ±25% have been recorded [46]. Process controlling parameters such as temperature, retention time, volumetric loading, technology deployed (*viz.*, continuous versus batch, single versus two stage digestion, slurry feeding cycle and stirring technology, etc.), and degree of pre-treatment of feedstock are important. Feedstock type is also important, e.g., fat, proteins and sugar contents have high methane yield [47]. On the other hand, inhibitors such as ammonia and lipids in waste streams from abattoirs can significantly derate yield [48]. Stage of energy crop harvest, weather and soil growth conditions may also affect biogas yield. Whereas theoretical calculations of biogas yield on the basis of fat, carbohydrates and protein contents are straightforward [49], accurate energy audit should be based on realistic data that can be validated against performance of full-scale plants. Analyses in this study for single feedstock digestion were based on biogas business planning data (Table 5) compiled by the Association for Technology and Structures in Agriculture (KTBL) in Germany [49]. Biogas yield in co-digestion was estimated to be ca. 10% higher that yields from single feedstock digestion (Fig. 3).

3.2. Considerations in feedstock supply logistics

Table 6 shows the energy input data for crop cultivation and straw recovery. Straw recovery considered only agricultural machinery fuel consumption during baling operation. Energy crop feedstock considered land preparation, seeding, fertilizer and pesticide application, and harvesting operations. Utilization of industry waste, MSW, and food waste considered pre-treatment and/or sterilization [50], including the removal of contraries like metal and sand, and final pulping to fluidise the fibrous matter [51]. Related energy inputs are given in Table 7.

3.3. Energy input to feedstock transportation

The primary energy inputs to feedstock collection and transportation considered: diesel fuel consumption per tonne per kilometre transported (tkm), and customized refuse trucks with empty return trips, omitting any secondary transport logistics [52]. Fuel consumption for the transportation of agricultural feedstock was determined by bands of distance covered, i.e., $\leqslant$2 km, 2 $\leqslant$ 20 km, and >20 km (Table 8). The quoted values cover loading processes.

Fuel consumption associated with waste collection depends on factors such as, collection area, distance, traffic situation, number of stops etc. The primary energy input for collection and transportation of MSW and residues from food industry was separated into energy inputs for waste collection and for transportation between the collecting areas and designated biogas plants. Solid organic waste was source separated. Table 9 shows the energy input to collection and transportation of MSW; the collection component considered energy requirement for lifting bins and compacting the waste [53,54]. Collection and transportation of industrial organic waste streams (Table 10) assumed lesser automated handling operations and fewer number of stops compared to MSW [55].

Table 6
Energy inputs for energy crop cultivation and straw recovery [15,80].

Parameter	Corn silage[a]	Grass silage[a,b]	Whole wheat plant silage[a]	Straw[a]
Estimated yields ($t_{DM}\ ha^{-1}$)	16	8	14.5	3.3
Seeds ($MJ_{PE}\ t_{DM}^{-1}$)	15	91	43	–
Cultivation/recovery ($MJ_{PE}\ t_{DM}^{-1}$)	294	732	311	140
Fertilizer				–
Nitrate N ($MJ_{PE}\ t_{DM}^{-1}$)	358	1108	711	–
Phosphate P_2O_5 ($MJ_{PE}\ t_{DM}^{-1}$)	78	155	120	–
Potassium oxide K_2O ($MJ_{PE}\ t_{DM}^{-1}$)	58	116	89	–
Lime CaO ($MJ_{PE}\ t_{DM}^{-1}$)	133	5	148	–
Pesticides ($MJ_{PE}\ t_{DM}^{-1}$)	44	0	49	–
Total energy input ($MJ_{PE}\ t_{DM}^{-1}$)	*980*	*2207*	*1471*	*140*

[a] Corn, grass and wheat losses in ensilage were assumed to be 10% [14] and straw losses in storage 5% [89].
[b] Permanent grasses: 4 harvests per year.

3.4. Biogas plant operation

Energy input to biogas plant operation varies with feedstock type and deployed technology, but higher degree of automation in large-scale biogas plants require relatively higher energy input [56]. Energy input to plant operation also depends on; required stirring to maintain slurry homogeneity and ease biogas release, pump rating (liquid feedstock) and conveying (solid feedstock), the feeding frequency, and energy rating of auxiliary equipment. Easily bio-degradable feedstock require higher feeding frequency to maintain stability of the AD process [38].

Heat demand for AD in mesophilic temperature range (30 and 37 °C) depends on, among other factors: the integrity of thermal lagging of the digesters; location of digesters (underground or free-

Table 7
Energy inputs for pre-treatment and sterilization of feedstock.

Feedstock		Electricity[a] ($kW\ h_{el}\ t^{-1}$)	Heat[b] ($kW\ h_{th}\ t^{-1}$)
MSW	Pre-treatment	60	
Slaughterhouse waste (paunch content)	Sterilization (20 min, 133 °C, 3 bar)		31.5
Food residues	Pre-treatment and sterilization (1 h, 70 °C)	24	22.4

[a] Average electricity demand of 150 $kW\ h_{el}$ per tonne dry matter for pre-treatment of feedstock. Data based on [55,76].
[b] 10% and 15% of waste heat from biogas-to-CHP generation was used for sterilization of food residues and slaughterhouse waste (paunch content), respectively [50].

Table 8
Energy inputs for transportation of agricultural feedstock.

Feedstock	Energy inputs by distance band[a,b] (MJ_{PE} t km^{-1})		
	short distance ⩽ 2 km	mid-range distance 2 km ⩽ 20 km	Long distance >20 km
Cattle manure	3.2	2.8	2.1
Straw	15.1	6.9	4.4
Corn silage	12.6	7.5	4.4
Grass silage	8.8	3.7	2.5
Whole wheat plant silage	5.4	3.7	2.5

[a] Using agricultural transporter consisting of tractor and trailer.
[b] Data based on [17,80].

Table 9
Energy input for collection and transportation of Municipal Solid Waste (MSW).

Operation	Collection and transport MJ t_{DM} km^{-1}	Distance driven km	Energy input MJ t_{DM}^{-1}
Collecting urban areas[a]	45	15	675
Transportation urban[c]	3.9	5	19.5
Collecting rural areas[b]	25	40	986
Transportation rural[c]	3.9	5	19.5

[a] Collection predominantly for large-scale biogas plants; Data based on [13,76,90].
[b] Collection predominantly for small-scale biogas plants; Data based on [13,76,90].
[c] Transportation distance between collection area and designed biogas system was assumed to be 5 km. Data based on [52].

Table 10
Energy inputs for collection and transport of industrial organic waste streams.

Feedstock	%DM	Energy input		
		Truck load (t)	Collection[a] (MJ t_{DM} km^{-1})	Transportation[b] (MJ t km^{-1})
Food residues	16	20.5	20.7	1.8
Pomace	22	15.3	17.9	2.1
Slaughterhouse waste (paunch content)	15	15.3	26.2	2.1
Grease separator sludge	5	10.5	100.8	2.7

[a] 50% efficiency, return trip empty. Collection for small and large-scale biogas plants was assumed to be 40 km (rural area) and 15 km (urban area), respectively. Data based on [52].
[b] Outward trip full, return trip empty. Distance between collecting area and designed biogas system was assumed to be 5 km. Data based on [52].

standing); seasonal variations in heat demand, and feedstock type. Energy input for feedstock sterilization (Table 7) and heating digesters was serviced from the plants' own generation capacity (e.g. CHP). Process heat in case of biogas upgrading to biomethane was provided from fossil fuels (Table 1). The proportion of process heat demand for small-scale biogas plants was assumed to be higher than for large-scale plants (Table 11), due to less efficient lagging of digesters [4].

Wet digestion process was deployed for feedstock DM content of up to 12%, to allow for pumping and stirring [39]. In the calculation of primary energy input for individual feedstock, it was assumed that 12% DM corresponded to 1 tonne of feedstock mixture. Therefore, 1 tonne of cattle manure with 8% DM content was assumed to correspond to 0.7 tonnes of feedstock mixture, generating 0.7 tonnes of digestate, whereas 1 tonne of MSW (40% DM) corresponded to 3.3 tonnes of mixture and generating equivalent amount of digestate. The DM content of 12% was achieved by dewatering feedstock using screw-press technology or adding water, and accounting for 19 and 32 MJ_{PE} per tonne for small and large-scale biogas systems, respectively [57].

3.5. Biogas utilization

3.5.1. Electricity generation

3.5.1.1. Combined Heat and Power (CHP) generation. Biogas-to-CHP represents the most common utilization in Germany. The generated electricity is fed into the national grid, while the heat may be consumed via district heating networks, with typical transmission losses presented in Table 12. Part of the generated heat is used in the AD process control, and for sterilization of feedstock, if required. Efficiencies of CHP units and respective energy inputs considered are presented in Table 13.

3.5.1.2. Fuel cell technology. Deployment of fuel cell technology is at an advanced development status in Germany [58]. Due to their high efficiency, low emissions and multiple fuel possibility, the Molten Carbonate Fuel Cell (MCFC) is considered one of the most promising [59]. However, it is recognised that related investment costs are still high [60], therefore commercial deployment is yet to be achieved [58]. A heat transmission distance of 2 km was assumed as typical for heating of green houses in horticulture (Table 12). Energy input to MCFC was equivalent to 2% of electricity generated [61], with electrical and thermal efficiencies of 50% and 40%, respectively [59,62,63].

3.5.1.3. Stirling engines. Stirling engines are non-fuel specific external combustion engines that require very little maintenance [64]. For units up to 100 kW_{el}, electrical and thermal efficiencies are 24% and 72%, respectively, which makes heat utilization attractive

Table 11
Energy inputs for biogas plant operation considered.

	Proportion of energy inputs for biogas plant operation, %	
	Electricity demand	Heat demand
Small-scale biogas plant		
(a) Energy input as proportion of electricity produced in CHP (%)[a]	4	25
(b) Energy input as proportion of biogas produced (%)[b]	1.3	12.5
Large-scale biogas plant		
(a) Energy input as proportion of electricity produced in CHP (%)[a]	7.5	20
(b) Energy input as proportion of biogas produced (%)[b]	3	9.6

[a] Implementation in case of single feedstock digestion and feedstock co-digestion scenarios. Data based on [56,91].
[b] Implementation in case of upgrading biogas for substitution of natural gas and utilization as transportation fuel. Data based on [56,91].

Table 12
Estimated heat losses in district heating network; transmission losses depend on thermal volume flow rate and transmission distance [49,61].

	Estimated loss by transmission distance, %			
	0.5 km	2 km	3 km	5 km
Small-scale biogas plants (%)	3.5	13.5	20	32
Large-scale biogas plants (%)	1	4	6	10

Table 13
Efficiency and electricity inputs for CHP generation from biogas.

	Efficiency and electricity input for CHP generation, %		
	CHP electrical efficiency[a]	CHP thermal efficiency [a,b]	Electricity input running CHP[c]
Small-scale biogas plant (%)	33	50	3
Large-scale biogas plant (%)	40	48	4.5

[a] Data based on [39,92].
[b] Whereas the thermal efficiency is always higher than electrical efficiency for all CHP units, the thermal efficiency of large-scale units is typically lower than of small-scale units [39]. Up to 40% electrical efficiency has been reported for CHP units >0.7 MW_{el} electrical output [49,92].
[c] Electricity input is calculated from electricity produced by CHP [56].

[4,64,65]. Maximum heat transmission distance of 0.5 km was assumed (Table 12). Biogas purification is not necessary; therefore, energy input of 2% of electricity generated was assumed [66–68].

3.5.1.4. Micro gas turbines. Modular micro gas turbine modules are rated at 30–200 kW and can be readily combined in multiples to meet specific load requirements [69]. Their lower combustion temperature results in lower NO_x emissions [4,70]. The study assumed electrical and thermal conversion efficiencies of 28% and 54%, respectively [49], and heat transmission over 0.5 km (Table 12). Since they require purified compressed biogas, energy input of 10% of the electricity generated was assumed [66,71].

3.5.2. Heat generation

3.5.2.1. Process heat demand of biogas system. Energy demand for heating the digesters typically ranges between 20% and 25% of total heat component from CHP generation. Based on stipulated pretreatment conditions (Table 7), sterilization of food residues and slaughterhouse waste consumed 10% and 15% of total heat, respectively. Therefore, approximately 50% of generated heat was available for plant processes including internal losses, and the balance was available for external use.

3.5.2.2. Heat utilization via district heating network. External heat utilization via district heating networks included space heating (houses, animal stalls, greenhouses, and public amenities) near to the generating biogas system. Heat demand will vary with season, e.g., horticulture in greenhouses typically requires heat for up to 5200 h a year [72], therefore, sustained use of 60% of the heat available for external use (30% of total) was assumed. Energy input to transmission pumps equivalent to 2% of the useful heat was assumed [61].

3.5.2.3. Organic Rankine Cycle process. The Organic Rankine Cycle (ORC) process converts thermal energy from low temperature heat sources to electricity using organic fluids of high molecular mass. Application is recommended for biogas plants with output exceeding 300 kW_{th} [73], and where there is no demand for heat. The heat-to-electricity conversion efficiency varies between 5% and 17% [65,74], but average efficiency of 12% was assumed. About 20% of thermal energy from associated CHP generation was available for ORC process [61]. High annual usage and high system reliability are pre-requisites for economic operation of ORC units [74]. Investment cost are approximately 60% of equivalent Stirling engine [75].

3.5.2.4. Other areas for biogas utilization. Absorption chillers provide additional possibility for utilization of waste heat in combined heat, power and cooling (tri-generation). Absorption chillers transform waste heat to cooling energy with an efficiency of ca. 70%, and typical energy input is 70 kW h_{el} per MW h of cooling energy load [73]. It was assumed that 40% of useful heat is available for cooling, and replaces electricity generated from fossil fuel mix (Table 1). The generated heat from biogas systems can also be used for applications such as drying of agricultural produce and the digestate. The latter was estimated to require 623.5 MJ per tonne [49,76].

Table 14
Energy input and heat demand for upgrading of biogas.

	Energy input (MJ m^{-3}_{biogas})	Energy input (MJ $t\,km^{-1}$)
Electricity input[a]	1.1	
Heat demand[a]	0.36	
Compression to 1.6 MPa[b]	0.18	
Transmission of gas[c]		0.2
Compression to 20 MPa[d]	0.47	

[a] Data based on [61].
[b] Pressure required for injecting into natural gas grid [29,49].
[c] Transmission distance to the natural gas network of 0.5 km was assumed [52].
[d] Pressure required for using on filling stations [29,49].

3.5.3. Upgrading of biogas

Upgrading of biogas to biomethane and, where regulations permit, injecting into the natural gas grid is an efficient way of integrating the biogas into the energy sector [77,78]. Biomethane can then be used as substitute for natural gas and as transportation fuel [79]. Both utility are still unregulated in Germany, which makes the determination of long-term viability unreliable [5]. Biomethane compression to 20 MPa in appropriate cylinders for transport fuel consumes additional energy input [61], but it was assumed that energy input per m^3 for cylinder transportation to vending stations was negligible [7]. Table 14 shows estimates of related energy inputs.

3.6. Processing and handling of digestate

Sustainable biogas utilization requires closed cycle of matter, encompassing the complete recycling of digestate [5]. For large-scale biogas plants, limitation on the amount of nutrients that may be spread on agricultural land [80] dictates the amount of digestate that can be safely recycled. Efficiency of digestate transportation may be enhanced by on-site processing into chemical fertilizer substitutes (decanter or screw-press was used for separa-

Table 15
Energy inputs in processing and handling of digestate.

	Activity	Energy input ($MJ_{PE}\,t^{-1}$)	Heat demand ($MJ_{PE}\,t^{-1}$)	Energy input ($MJ_{PE}\,t\,km^{-1}$)
Separation[a]	Decanter	74.3		
	Screw-press	4.3		
Liquid fraction and digestate[b]	Loading	0.63		
	Transport			2.84
	Spreading	20.16		
Solid fraction	Loading[b]	3.78		
	Transport[b]			3.15
	Spreading[b]	25.83		
	Drying[c]	130	623.5	
	Composting[d]	510		

[a] Decanter (high speed centrifuge) and screw-press technology, which separate solid from liquid fraction of digestate. Data based on [37,49].
[b] Data based on [80,93].
[c] Heat load for drying conveyor is met by output from CHP unit. Data based on [49,76].
[d] Average energy input for closed composting with main and pre-composting creating commercial fertilizer. Data based on [49,52].

tion). For example, separation of solid and liquid phases can reduce transportation requirement by up to 60% and another 25% after drying [23,76,81].

Digestate separation, loading, transport, and spreading on arable land account for the primary energy input in processing and handling. In this study, typical field machine working width, payloads and travel distance between biogas plant and field were considered [80]. Solid fraction can also be composted for approximately 60 days or alternatively dried with hot air supplied from the system, then used as substitutes for chemical fertilizer. Typical digestate constituents from co-digestion of mainly industry waste and MSW are 4.6 kg N, 1.8 kg P_2O_5 and 3.8 kg K_2O (DM 5.7%) per tonne. The liquid fraction can re-circulated in the AD process, spread out to the fields, or disposed in sewage treatment plant as was assumed in this study.

Residual biogas in digestate tanks can be up to 10% of biogas yield from the main AD process [4]; therefore, potential recovery from digestate storage was also considered. Table 15 outlines energy input to digestate processing and handling.

4. Results and discussion

4.1. Consideration of the single feedstock digestion scenario

Fig. 4 shows that the Primary Energy Input Output ratio (PEIO) in the single feedstock scenario ranged from 10.5% to 64.0% depending on feedstock used. Feedstock with low energy density like cattle manure (base scenario) required relatively higher primary energy input compared to primary energy output (Table 5). Fig. 5 shows that for single feedstock, biogas plant operation was generally the most energy-demanding process, and proportion on energy input ranged from 7.0% (grease separator sludge) to 53.9% (straw). The disparities were attributed to difference in DM content, e.g., 5% for grease separator sludge and 86% for straw (Table 5).

Energy crop cultivation and feedstock pre-treatment accounted for a high proportion of the primary energy input. Fig. 5 shows that for whole wheat plant silage, cultivation process was the most energy demanding (57.9% of total primary energy input) in comparison to cattle manure or grease separator sludge which do not require pre-treatment. It was also shown that the difference in energy input associated with feedstock collection and transportation, and digestate processing and handling can be significant. Such relate to transportation efficiency, hence, the amount of digestate generated per tonne of feedstock. For example, Fig. 5 shows that the proportion primary energy input for transport of cattle manure feedstock (175 $MJ_{PE}\ t_{DM}^{-1}$; 5.3%) is significantly lower than for digestate processing and handling (1137 $MJ_{PE}\ t_{DM}^{-1}$; 34.7%). This is explained by additional energy inputs for loading and spreading of digestate. Feedstock collection and transport of MSW and slaughterhouse waste accounted for higher proportion of primary energy input (32.8% and 26.5%, respectively) than handling of the respective digestate (5.0% and 15.7%, respectively), due to the additional feedstock collection operations.

The data shows that the differences in total primary energy input to feedstock supply logistics is influenced by origin and characteristics of feedstock. For example, whereas feedstock from known waste streams such as cattle manure, and industrial waste that do not require sterilization (e.g. pomace and grease separator sludge),hence, only required energy input for collection and transport; energy crops required additional input for cultivation and harvesting of the crops (Fig. 5). Other feedstocks like MSW, food residues and slaughterhouse waste require energy-demanding pre-treatment processes before they can be used for biogas production.

Fig. 6 shows that the PEIO varies considerable with transportation distance for feedstock and digestate. It shows that the transportation distances for grease separator sludge and cattle manure to trigger negative energy balance were less than 17 and 22 km, respectively. For cattle manure, the low value was attributed to the lower specific biogas yield (297 $m^3\ t_{DM}^{-1}$) combined with expected low transportation efficiency due to low DM content of digestate (Table 5). The high biogas yield from grease separator sludge would be expected to allow for efficient transportation and therefore capable of maintaining a positive energy balance over longer distances (Table 5). However, it was observed that energy input to feedstock collection and transport, and digestate processing

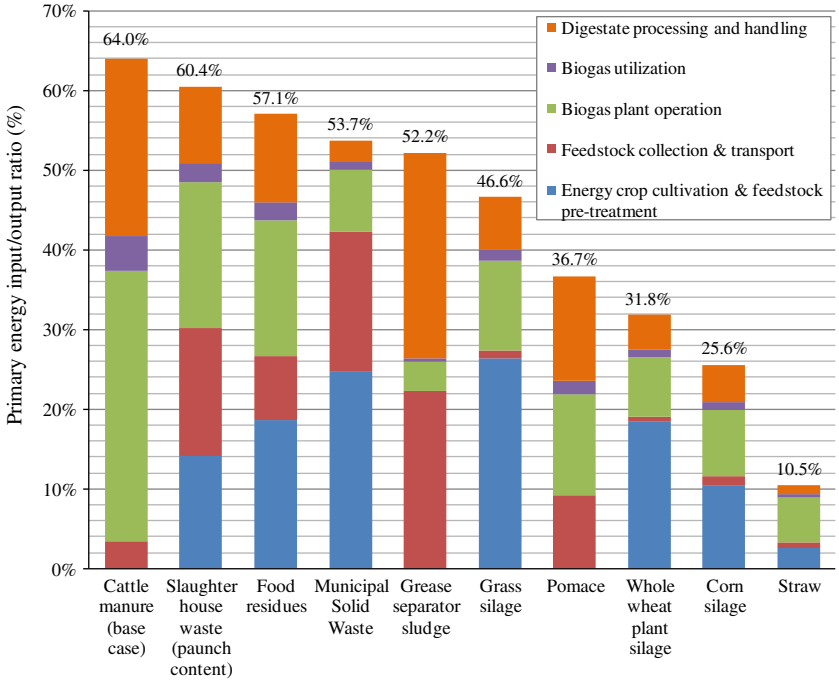

Fig. 4. Primary Energy Input Output (PEIO) ratio in single feedstock digestion scenario.

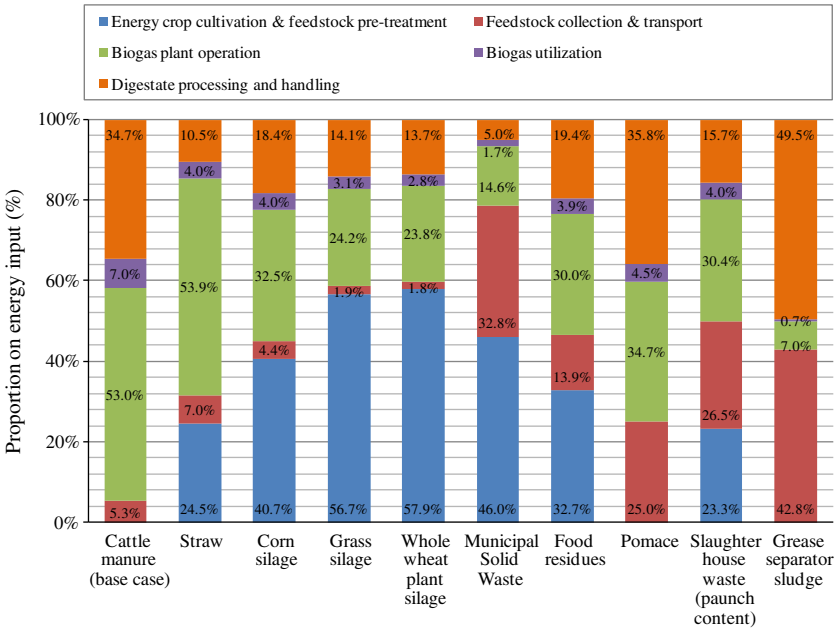

Fig. 5. Proportion of energy input to process steps by single feedstock digestion scenarios.

and handling equated to 92.3% of total energy input (Fig. 5). For slaughter house waste, corn silage and whole wheat plant silage, the primary energy balance was estimated to turn negative for transportation distances in excess of 72, 345 and 460 km, respectively. These could be attributed to their relatively high biogas yield (Table 5) coupled with more energy efficient transport regime, consuming only 15.5–42.2% of total energy input (see Fig. 5). The outlined observations indicate the importance of local sourcing of feedstock and/or disposal of spent digestate. They also underline importance of diversified feedstocks, therefore necessity for co-digestion regimes.

4.2. Consideration of feedstock co-digestion scenario

Fig. 7 shows the PEIO for co-digestion scenarios analysed based on realistic feedstock proportions described in Table 2. The estimated PEIO ranged between 45.6–48.6% and 34.1–55.0% for small and large-scale biogas systems, respectively. The spread in PEIO values were lower than for single feedstocks (10.5–64.0%; Fig. 4), which suggests more stable processes. Fig. 8 shows that in co-digestion, biogas plant operation was still the most energy-demanding process.

For Base SS-1, 70% of the total feedstock mixture was derived from energy crops consuming 860 $MJ_{PE}\ t_{DM}^{-1}$ (20.4%) for cultivation process compared to 440 $MJ_{PE}\ t_{DM}^{-1}$ for Base SS (12.5%) cultivating only 45% corn silage of co-digestion mixture (Table 2). The proportion of energy input towards feedstock collection and transport in Base SS-2, co-digestion of agricultural waste with industrial waste streams was five times higher (20.8%) than for Base SS digesting cattle manure with corn silage (4.1%; Fig. 8). This disparity could be attributed to a high feedstock proportion (Base SS-2; 55%) delivered by a more elaborate collection and transportation regime from private households and industry (Table 9 and Table 10) compared to handling and delivery of feedstocks primarily from agri-

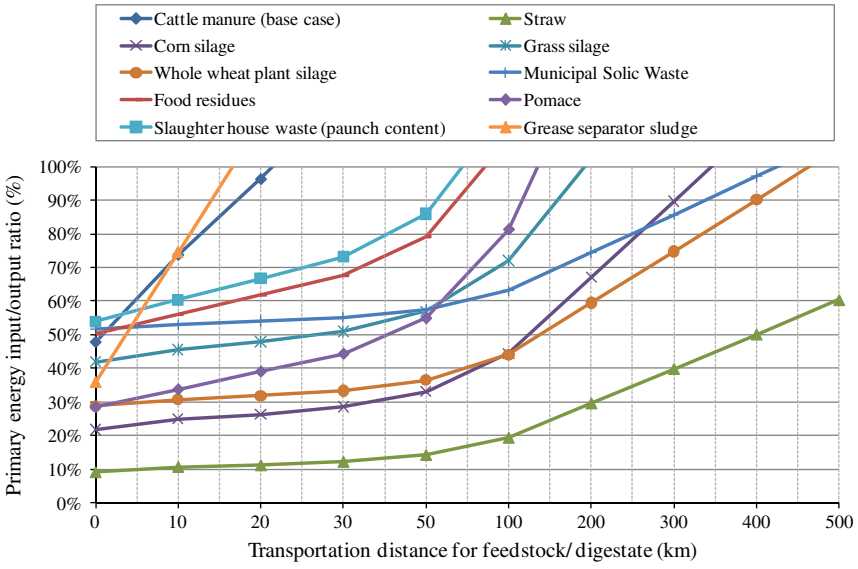

Fig. 6. Primary Energy Input Output (PEIO) ratio of single feedstock digestion scenario as a function of the transportation distance. It was assumed that digestate has to be transported the same distance as feedstock.

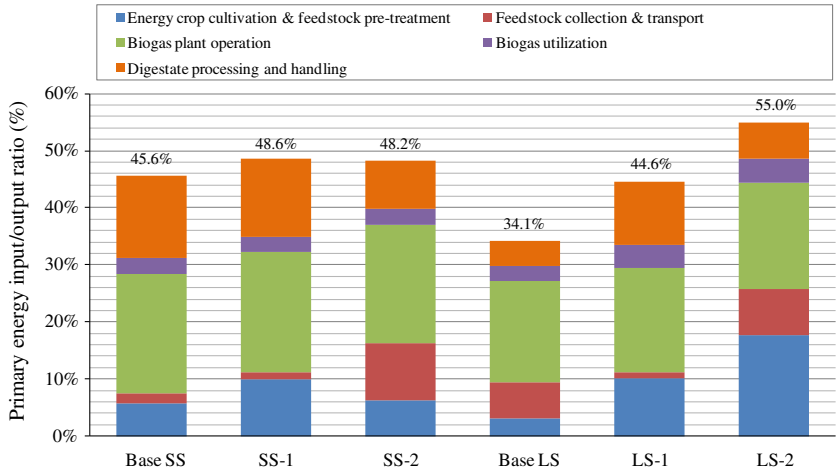

Fig. 7. The influence of co-digestion of multiple feedstocks on Primary Energy Input Output (PEIO) ratio for small and large-scale biogas systems (primary energy output: Base SS: 7.8 $GJ_{PE}\ t_{DM}^{1}$ and Base LS: 17.3 $GJ_{PE}\ t_{DM}^{-1}$).

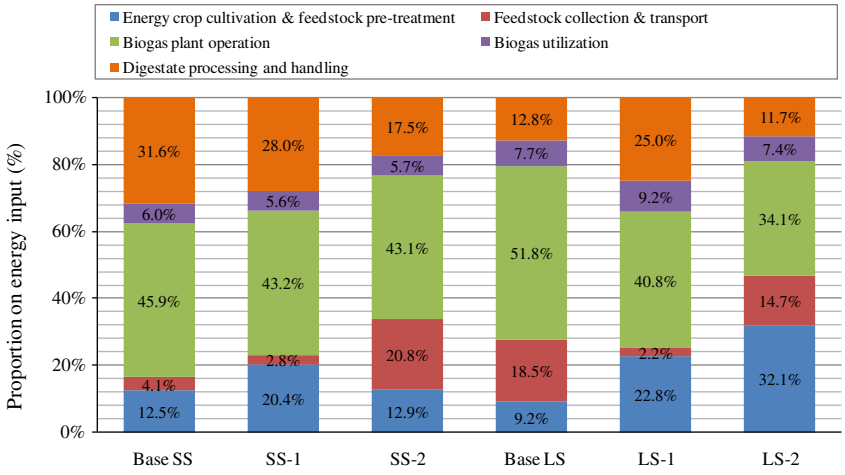

Fig. 8. Proportion of energy input to process steps by designed feedstock co-digestion scenarios for small and large-scale biogas systems.

cultural waste scenarios (Table 8). For Base SS-1, co-digestion of mainly energy crops with high DM content (Table 5) required dilution to achieve 12% DM of feedstock mixture, which resulted in higher volume of digestate to handle (28%; 1200 $MJ_{PE}\ t_{DM}^{-1}$) than the original feedstock digested (2.8%; 120 $MJ_{PE}\ t_{DM}^{-1}$) (Fig. 8).

Fig. 8 shows that energy input for feedstock pre-treatment in Base LS accounted for 9.2% (550 $MJ_{PE}\ t^{-1}$), whereas in Base LS-2 it accounted for 32.1% (1450 $MJ_{PE}\ t^{-1}$). The difference could be attributed to the higher proportion of feedstock designated for mandatory pre-treatment/sterilization (Table 7). In contrast, only to 38% of feedstock combinations in Base LS scenario had mandatory pre-treatment/sterilization requirement (Table 2). The results also showed that more than double the primary energy output is realized from co-digestion of industrial waste streams in large-scale biogas plants (Base LS, 17.3 $GJ_{PE}\ t_{DM}^{-1}$) compared to agricultural feedstock (Base SS; 7.8 $GJ_{PE}\ t_{DM}^{-1}$). Higher fat content in grease separator sludge and food residues digested in Base LS probably accounts for the high biogas yield recorded in Table 5.

4.3. Consideration of biogas utilization scenario

Fig. 9 depicts the influences of biogas utilization (energy conversion) pathways on the PEIO, considering only the base case scenarios defined in Table 3 (Base SS, Base LS). Fig. 10 shows the proportion of energy input to process steps by designated utilization pathways. Fig. 11 depicts the savings in primary energy for different utilization pathways resulting from substituting different fossil fuels used in feedstock-to-biogas process (Table 1). The energy output of co-digestion scenarios Base SS and Base LS (Table 2) substitute electricity, heat, natural gas and transportation fuel within different biogas utilization pathways for small-scale and large-scale biogas systems, respectively (see Table 5, Fig. 3, Section 3.5). The generated energy from biogas (electricity, heat, biomethane) substitute fossil energy sources in the same area, and therefore, the primary energy inputs needed to produce fossil fuel based resources (Table 1). Calculation of the primary energy substitution of fossil fuels like natural gas with biomethane was based on their calorific values [82].

The results show that the PEIO in biogas utilization pathways for small and large-scale plants typically ranged between 4.1–45.6% and 1.3–34.1%, respectively (Fig. 9). The ranges of variation arise from the difference in efficiency of the respective energy conversion systems and substitution of different fossil fuels used in feedstock-to-biogas process (Table 1; Fig. 11). The range of variation in each case depicts the inherent potential for enhancing efficiency in biogas utilization.

Fig. 10 shows that the proportion of energy input to biogas utilization ranged between 6.0% (Base SS) and 18.1% (Base SS-f),

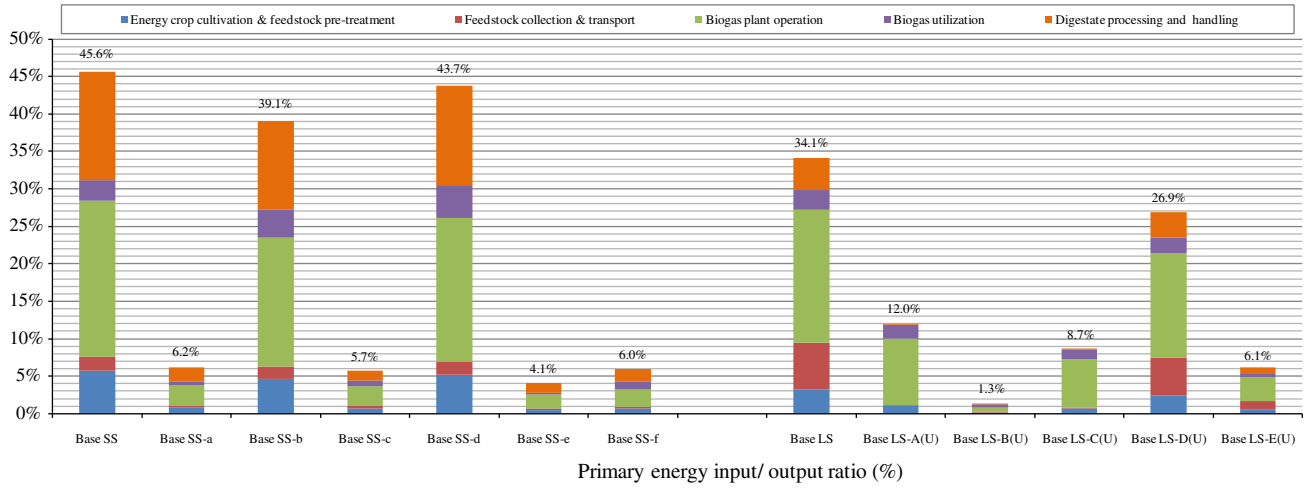

Fig. 9. The influence of different biogas utilization pathways on Primary Energy Input Output (PEIO) ratio for small and large-scale biogas systems.

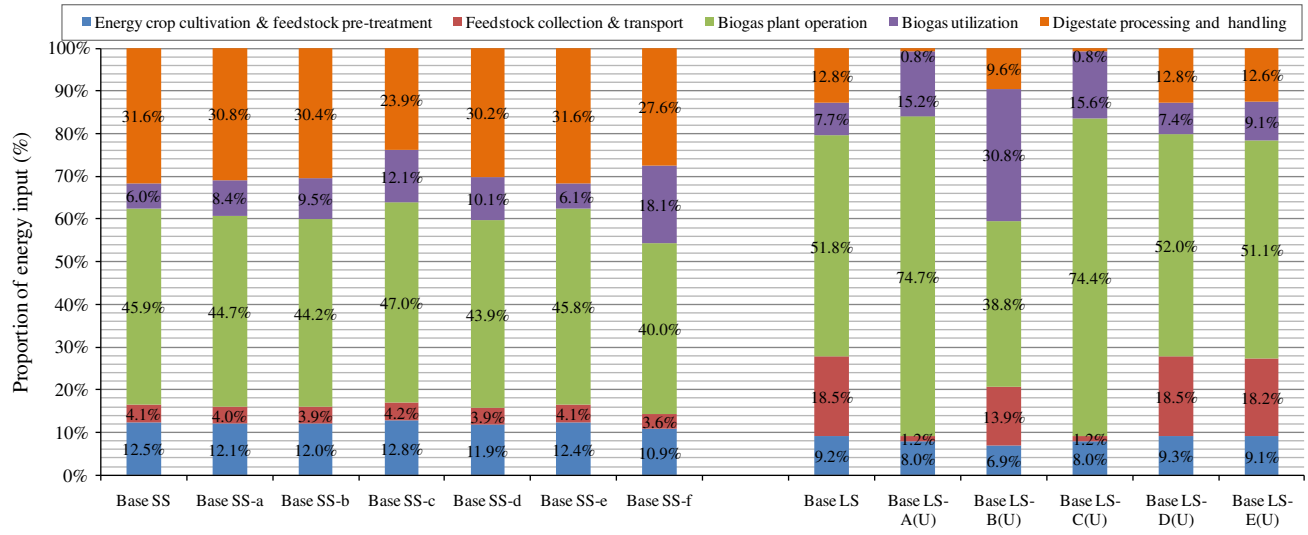

Fig. 10. Proportion of energy input to process steps by designated biogas utilization scenarios.

depending on process energy requirements and efficiency of different technologies. For example, energy conversion with a Stirling engine coupled with heat utilization in Base SS-e scenario required 215 MJ_{PE} t^{-1} of total energy input; whereas, the energy conversion with Micro gas turbine in Base SS-f was thrice the amount at 735 MJ_{PE} t^{-1} (Fig. 10). These results suggest that the most energy efficient conversion pathway (lowest PEIO) for small-scale biogas plants is the Stirling engine with utilization of the generated heat (Base SS-e: 4.1%, Fig. 9). This observation was mainly attributed to the high thermal efficiency of the Stirling engine (72%). The utilization of waste heat for secondary electricity generation with ORC process recorded only a marginal gain in PEIO (*cf.* Base SS-d at 43.7% versus Base SS at 45.6%). Therefore, the ORC technology may only be recommended for systems that do not include heat applications in the vicinity of a biogas plant (Fig. 9). Available data also suggests that the most viable utilization pathway for small-scale biogas systems compared to Base SS is CHP generation with external heat utilization (Base SS-a; 6.2%) at relatively short transmission distance (approximately 2 km). Heat may be coupled to provision of cooling energy (Base SS-c) on demand, which bears a marginal (0.5%) decrease in PEIO. Energy input to biogas utilization for large-scale biogas plants ranged from 7.4% to 30.8% (Fig. 10). The savings in primary energy input by substitution of process fossil fuel (natural gas) with portion of generated biogas increased by a factor of nine (754,700 MJ t_{DM}^{-1}) in case of Base LS-A(U) against 87,200 MJ t_{DM}^{-1} (Base LS) substituting mainly electricity produced from German electricity mix and fossil fuel mix for internal process heat (Section 3.5.2; Fig. 11).

The use of biomethane as transportation fuel (Base LS-C(U)) represents an attractive utilization pathway with PEIO of 8.7% (Fig. 9). However, the number of filling stations in Germany and varying costs for transportation of compressed gas are still limiting factors [7]. In preparation of biomethane for injection into natural gas network (Base LS-A(U)), the proportion of energy input for biogas plant operation increased by 22.9% compared to base case with 51.8% (Fig. 10). This was attributed to digester heating demand, and feedstock sterilization and gas upgrade technology based on fossil fuels (Table 1). With coupled small-scale CHP unit (Base LS-B(U)), where part of waste heat is used for heating the digester(s) instead of fossil fuels, the energy input for plant operation was almost halved to 38.8% compared to Base LS-A(U) (Fig. 10). Based on the outlined analyses, the most energy efficient conversion pathway for large-scale biogas systems include: (i) upgrading of biogas specifically for gas grid injection, but using small-scale CHP to service process and biogas upgrading energy loads (estimated PEIO 1.3%) and (ii) fuel cell technology with heat utilization (estimated PEIO 6.1%).

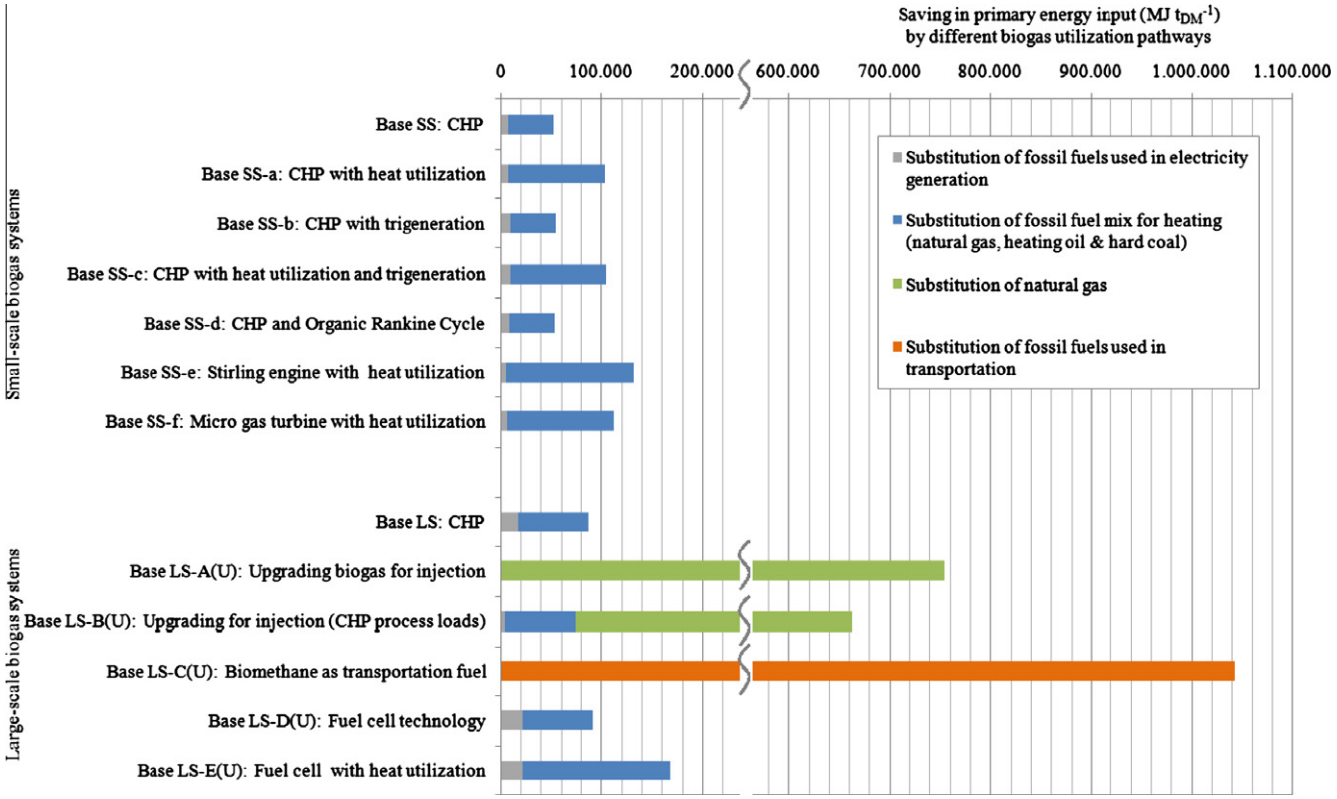

Fig. 11. Savings in primary energy by substitution of fossil fuels with portions of generated biogas for the different biogas utilization pathways considered.

Both could meet the heating requirement of the biogas plants from the waste heat generated during conversion.

4.4. Consideration of waste stream scenario

Fig. 12 depicts the influence of digestate treatment and handling scenarios described in Table 4 on PEIO. Fig. 13 shows the energy inputs for processing and handling, whereas Fig. 14 shows the influence of digestate separation on transportation efficiency.

The results in Fig. 12 show that the digestate processing and handling method alone could enhance PEIO by up to 8.7% (Base LS-D(W)b), compared to the base scenario analysed (34.1%). Fig. 13 shows that separation technology is key determinant of energy input. For example, for the treatment Base LS-A(W), up to 10.6% of energy input for digestate processing and handling

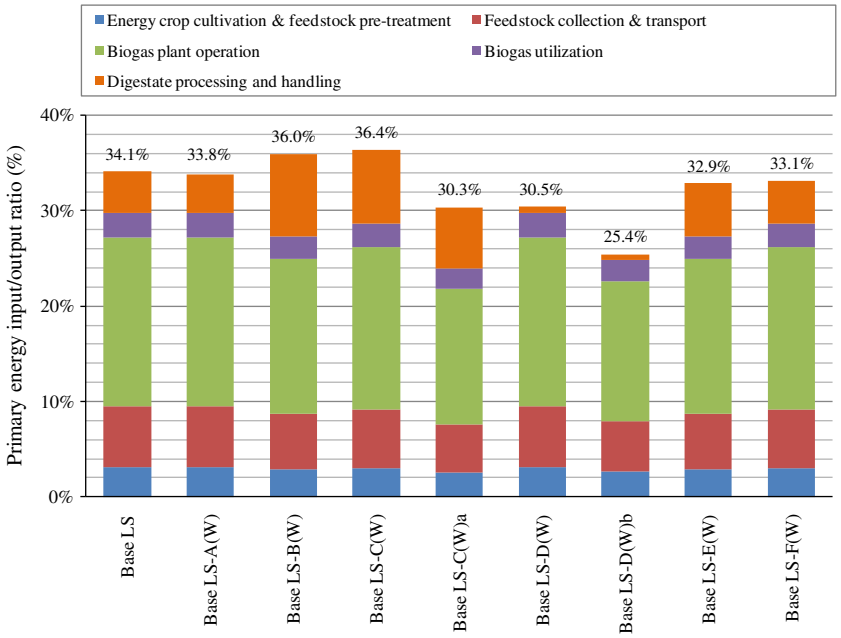

Fig. 12. Influence of different digestate processing and handling in biogas plants on Primary Energy Input Output (PEIO) ratio.

is consumed by decanter separation technology compared to up to 0.7% for screw-press technology in Base LS-D(W). Energy input for loading, transport and spreading of digestate depended on the consistency achieved by separation, drying or composting. For example, loading and transport, and spreading of digestate for Base LS was equivalent to 12.7% of primary energy input (756 MJ_{PE} t_{DM}^{-1}), whereas digestate flow rate reduction of ca. 60% limited the energy input to 1.6% (82 MJ_{PE} t_{DM}^{-1}) in case of Base LS-D(W).

It could be argued that requirement for dewatering of the digestate will depend on location of a biogas plant, i.e., whether digestate can be spread nearby biogas plant without dewatering, or if it is pre-requisite for enhanced transportation efficiency. Fig. 14 shows that dewatering of cattle manure and MSW by screw-press saves 50% of energy input for transportation within 40 km (47 MJ_{PE} t^{-1}) and 5 km (74 MJ_{PE} t^{-1}), respectively. For dewatering with a decanter (see Table 15), transportation efficiency within a 120 km distance increased by 34% and 42% for cattle manure and MSW, respectively.

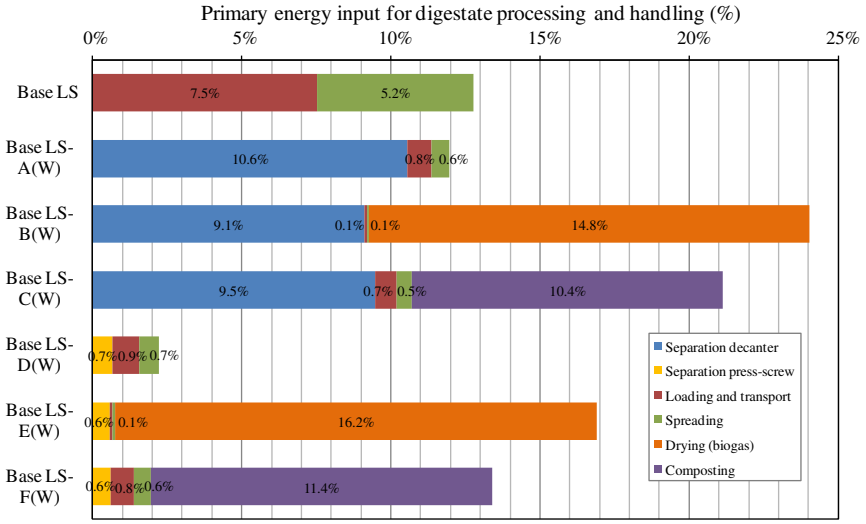

Fig. 13. Proportions on total primary energy input for different digestate processing and handling technologies within the waste stream scenario for large-scale biogas systems defined in Section 2.3.

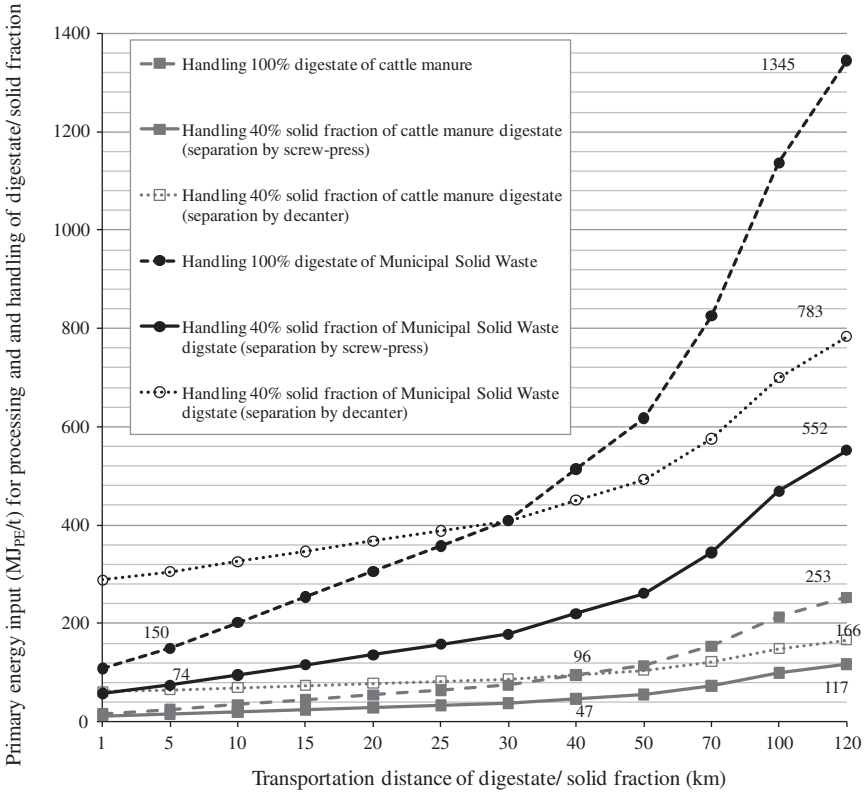

Fig. 14. Influence of digestate separation into liquid and solid fractions on transportation efficiency arising from enhanced handling for loading, transport and spreading.

The primary energy input for digestate processing and handling increased over and above the base scenarios considered, when digestate drying was required. Therefore, digestate drying is only viable when waste heat is available on-site. It was also shown that residual biogas utilization improved the PEIO by 6.1% and 5.1% in case of Base LS-C(W)a and Base LS-D(W)b), respectively.

Overall, implementation of new biogas plants does not always focus on high energy output alone. Substitution of fossil fuels, changes in agricultural land use, additional income options for farmers or alternative waste management systems to landfilling are key determinants of viability. For example, feedstock with high biogas yield may not always be available due to seasonal availability, legal restrictions (health and safety and environmental protection), energy-demanding pre-treatment requirements (e.g. abattoirs waste), or highly unstable AD process control that may not support sustained utilization. However, more efficient AD process and utilization of generated gas, combined with prolific waste-stream management can enhance feedstock-to-energy efficiency to foster sustainability.

5. Conclusions

Results from this study show that there could be significant variation in energy efficiency for biogas plants arising from feedstock resource and process adopted (single feedstock versus co-digestion), conversion technology applied, and digestate management technique. For single feedstock digestion, the Primary Energy Input to Output (PEIO) ratio ranged between 10.5% and 64.0%, depending on energy demand for feedstock supply logistics. For conditions analysed, the energy balances turned negative for transportation distances in excess of 22 km for cattle manure, 345 km for corn silage, and 425 km for MSW in single feedstock digestion scenarios, which could determine the most efficient sources of feedstock and subsequent disposal of digestate.

For co-digestion of multiple feedstocks, the PEIO ranged between 45.6–48.6% and 34.1–55.0% for small and large-scale biogas systems, respectively, which suggests more stable processes in co-digestion. The recorded PEIO for small and large-scale biogas utilization pathways ranged between 4.1–45.6% and 1.3–34.1%, respectively, depending on efficiency of the respective energy conversion systems and potential substitution of different fossil fuels, which indicates the inherent potential for energy efficiency enhancement. For example, most efficient utilization pathways for small and large-scale biogas plants was CHP generation with heat utilization at relatively short transmission distance (PEIO 6.2%) and upgrading of biogas specifically for gas grid injection, but using small-scale CHP to service process and biogas upgrading energy loads (PEIO 1.3%), respectively. Energy efficiency could be enhanced by up to 6.1% by recovery of residual biogas from enclosed digestate storage units. Energy performance of digestate management strategy depended on whether dewatering or drying was required to enhance transportation efficiency, but drying was sustainable only where surplus heat from energy conversion process was available.

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